ESD-TDR-65-72

Technical Report 389

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Millimeter Wave Research: Past, Present, and Future

17 May 1965

Prepared under Electronic Systems Division Contract AF 19(628)-500 by

Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
Lexington, Massachusetts

The work reported in this document was performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology, with the support of the U.S. Air Force under Contract AF 19(628)-500.

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LINCOLN LABORATORY

MILLIMETER WAVE RESEARCH: PAST, PRESENT, AND FUTURE

J. W. MEYER

Division 3

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ABSTRACT

This report is the edited transcript of a seminar given at Lincoln Laboratory on 2 March 1965. The cyclicity of interest in millimeter wave research is traced from the time of Hertz, when investigations of this part of the electromagnetic spectrum began. The waxing and waning of millimeter wave research are traced as exciting new fields are discovered which diverted the interest of physicists. Each re-emergence of millimeter wave research has been more robust, often because the results of the diversions were important to improved techniques. Early millimeter wave apparatus is described. The narrative of the development of a millimeter wave radar for the detection of the moon relates the opening of this spectral region to radar astronomy. Other applications are mentioned, along with future possibilities. A chronology, a list of large millimeter wave antennas, and a bibliography of review papers are included.

Accepted for the Air Force
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FOREWORD

MILLIMETER-WAVE CHRONOLOGY

1885	H. Hertz, Technishe Hochschule Fridericiano in Karlsruhe. Subject: $\lambda = 66$ cm.
1889	H. Hertz, Address at Heidelberg. Subject: cannection af light and electric waves.
1895	Peter Lebedev, Ann. Phys. Chem. (Leipszig) 56, 1 (1895). Subject: 6-mm Hertz oscillators.
1895	W.K. Roentgen, discavered X-rays (received first Nobel Prize in Physics, 1901).
1895-97	J.C. Bose, Subject: 5-mm spectrascapy.
1897	J.J. Thamsan, Subject: electran isalated.
1897	G. Marconi, Subject: communications over range of 4 mi. Hertz reflectars ot 25-cm wavelength.
1912	Max van Laue's discovery af X-ray diffraction in crystals (Nabel Prize 1914) (The Broggs 1915).
1912	Arkodiev, Physik. Z. 14, 928 (1913); Ann. Phys. 65, 643 (1912). Subject: 11 mm.
1920	W. Mäbus, Ann. Physik 62, 293 (1920). Subject: 7-mm Hertzian waves.
1923	E.F. Nichols and J.D. Tear, Phys. Rev. 21, 587 (1923). Subject: 2-mm and 0.22-mm Hg arc + interferometer. Astrophys. J. 61, 17 (1925). Subject: jaining the infrared and electric wave spectra.
1929	A. Glagoleva-Arkadieva, Subject: 50-mm and 129-µ mass ascillotors.
1933	C.E. Cleeton and N.H. Williams, Phys. Rev. 45, 234 (1934). Subject: NH_3 spectrum 10—40 mm.
1936	C.E. Cleeton and N.H. Williams, Phys. Rev. 50, 1091 (1936). Subject: the shortest continuous rodio woves. (6-mm mog.)
1950	J.R. Pierce, Physics Today orticle. Subject: millimeter waves.
1954	Gordan, Zeiger, and Townes, Subject: ommonio moser.
1957	J.R. Pierce, Electranics article. Subject: mm waves (spoke of little exploited gop).
1960	T. Maiman, Subject: laser actian in ruby.
1963	The opening af the MM Wave spectrum to radar astronamy, mm radar observatian af the moon.

MILLIMETER WAVE RESEARCH: PAST, PRESENT, AND FUTURE

I. INTRODUCTION

We should be interested in the little things in life. I think they are important. By the end of this report, you'll probably conclude that the only thing little about millimeter waves is the wavelength. Everything else, particularly the price, is pretty large.

Will Rogers would begin his routine with "All I know is what I read in the papers." What I have been reading in the "paper" recently hails a resurgency of research in millimeter waves. I looked into it to see if I could determine whether this resurgency was real or whether it was something cooked up by the press because material to print about lasers was getting scarce. A couple of articles in particular attracted my attention. One of them appeared in Aviation Week and Space Technology which said late last summer, that "Millimeter waves hold aerospace promise!" This was followed by an article in Electronics in January of this year to the effect that millimeter research is coming back in style. If it comes back in style, if it holds promise, it must have been out of style and it must not have held promise. Perhaps researchers in the field are downright fickle. To detect a trend or a cycle, perhaps we ought to see what the nature of the development of millimeter wave research has been, what some of the turning points were, what the reason for an apparently fickle following was, what have been the benefits or losses on account of waxing and waning interest. When we see history about to repeat itself, the urge is felt to look at the past to foretell the future. I haven't resisted this urge. Mrs. Betty Boyd and Dr. J. Mindel have helped in the historical inquiry into past millimeter wave research. Let us look at this past that is said to be prologue.

II. HISTORICAL REVIEW

Actually, we have had millimeter waves from the time of Hertz. Although Hertz himself didn't work at millimeter wavelengths, some of the Hertzians did. By Hertzian I mean one who was a follower of Hertz, and there were many. Sir Oliver Lodge was one of the better known Hertzians. Hertz worked at 66 cm, not an unfamiliar wavelength for today's heavy radars.

It all began in the late 1800's. The celebrated address by Hertz at Heidelberg in 1889 in which he explained the connection between his Hertzian wave and the electromagnetic waves of light drew widespread interest. At about that time, a Russian, Peter Lebedev,* used Hertz's technique, with a resonator as a filter for the spark gap, to select waves at a 6-mm wavelength from the broad spark spectrum. He reported on this work in 1895. Sir J. C. Bose of India was

* For references, see chronology in Foreword.

also working at 5 mm and conducted many quasi-optical (a term coined by Lodge) experiments such as measuring the double refraction in crystals. Some of the crystals Bose studied are of considerable interest now as possible materials for use in masers and lasers. One of these crystals, beryl, when containing a chromium impurity becomes emerald, has been especially interesting in this application.

With such a promising beginning, what happened? For one thing, Roentgen discovered x-rays, a feat rewarded with the first Nobel prize that was ever awarded in physics. At about the same time, J. J. Thomson isolated the electron and so the physicist branch of the Hertzians deserted the field in droves to study the electron, and to delve into the structure of crystals by means of x-rays. In the long run, we can't really say that these defections were wrong, but they did slow developments in millimeter wave research for the moment. The electron tube has become the basic generator of millimeter waves. X-rays have helped us to understand solid materials, the very underpinning of our burgeoning field of solid state electronics today. It was in 1912, of course, that Max von Laue discovered x-ray diffraction in crystals and the Braggs were to follow up with further work. A Nobel prize in 1914 for von Laue and for the Braggs in 1915 was a recognition of their work.

The physicists were not the only defectors. The young Italian, Marconi, had read Hertz's paper and concluded that it was so obvious from Hertz's paper that one could communicate with these waves that he was astonished that no one had suggested the possibility. In 1897, he demonstrated to the satisfaction of the Post Office Department in England that one could communicate over a distance of about four miles with Hertzian oscillators and receivers operating at about 25-cm wavelength.

The engineers, however, were to find life much easier and more conducive to very long range communications at much longer wavelength. They, too, departed the environs of millimeter waves.

Millimeter wave work reappeared in Russia in 1913 with the work of Arkadiev. He used Hertz oscillators at an 11-mm wavelength in his research, which was interrupted by World War I.

Again millimeter wave research had to climb out of relative oblivion, and we see a second resurgency in the decade of the 1920's. In Germany, W. Möbus worked at 7-mm wavelength, and for the first time we see the entry of Americans into the field with the work of E. F. Nichols and J. D. Tear in 1923. Nichols and Tear, working with a high-pressure mercury arc and interferometers, were able to close the gap, as they put it, between the infrared and the electric wave spectra. They worked in the band from 2 to 0.2 mm.

All the generators used so far are essentially incoherent. A quasi-coherency at some millimeter wavelengths was obtained by narrowing the spectrum with resonators. At the very short wavelengths, such resonators are difficult to contrive. Initially, the resonators were Hertz dipoles scaled down appropriately for the shorter wavelengths.

In the late 1920's, Mme. A. Glagoleva-Arkadieva, following the initial work of W. Arkadiev, developed electromagnetic waves with so-called "mass radiators" in the 50-mm to 129-micron region. Mass or particle radiators are small conducting particles excited by a spark discharge. The particles, distributed in oil, were continuously supplied to the spark gap, as we shall see later. The dominant features of the resulting spectrum could be changed by changing the size of the particles.

In the 1930's, infrared spectroscopists were working hard on the spectra of gaseous molecules, and in particular on some of the fine structure. The infrared apparatus had inadequate resolution for work on the inversion spectrum of ammonia. It was in 1933 that Cleeton and

Williams opened the field of microwave spectroscopy with their studies of the ammonia spectrum in the 10- to 40-mm region. Cleeton and Williams were probably the first to develop coherent 6-mm waves by using a split anode magnetron. They reported on this work in 1936.

It is interesting to note that from the field of microwave spectroscopy the first maser was born; indeed, the first maser employed ammonia gas as the working medium on the resonance originally explored by Cleeton and Williams.

Research and development on radar during World War II were dramatic in their drive and purpose as spurred on by an omnipresent necessity for victory in the air. In quest of resolution, researchers were led to shorter and shorter wavelengths. The K-band radar that was to provide superior resolution to that achieved at X-band was hit hard by resonance absorption in water vapor at 12.5 mm. The momentum of this work carried it into the 9-mm region, but the war ended before any systems were implemented at this new wavelength.

The legacy of apparatus and people skilled in short wave measurements have led to the remarkable growth of microwave spectroscopy since the war. The advances and benefits of this work are manifold.

Upon entering the decade of the 1950's, we found the electromagnetic spectrum becoming more and more crowded by all the communications-related services we had learned to devise. Most of this crowding was at the longer wavelengths. People began to point to new and unexploited territory at millimeter wavelengths. John Pierce, writing in Physics Today (1950), pointed to millimeter waves as a good area of research. What the field needed most, according to Pierce, was many good people in it. Calls of this kind have been periodically sounded time and again. In an article in 1957, John Pierce again repeated some of the problems confronting millimeter wave research. They were still essentially the same, yet the promise appeared great.

The year 1954 saw the development of the ammonia maser by Gordon, Zeiger, and Townes. We are well aware of the impact of this development on our current research. It was based on the earliest microwave spectroscopy ever done: on microwave spectroscopy born out of work near the millimeter wave region.

The events that followed were at a dizzying pace. The solid state maser appeared. Synthetic ruby crystals were made for use in solid state masers. Maiman, in working with optical pumping of ruby rods, detected laser action in 1960. This development resulted in the most recent large-scale defection of physicists from millimeter wave work. It is through developments of this kind, although they appear to be leapfrogging the millimeter wave region, that we may well solve the riddle of how to develop large amounts of coherent electromagnetic energy at millimeter and submillimeter wavelengths.

Again we have a case where the opening field that caused the defection from millimeter wave research was worth a Nobel Prize.

In 1963, a landmark in systems development achieved at Lincoln Laboratory took the form of millimeter wave radar observation of the moon. This was an accomplishment that showed that although the development of millimeter waves has been cyclic in nature, it's had ups and downs, and with each re-emergence of millimeter wave research, it has attracted the interest of a larger number of people. We have a broader basic background, a larger podium to stand on, if you will.

There has often been a bit of pessimism about the millimeter wave business. John Ramsey, for example, writing in the Proceedings of the IRE in 1958, had this to say:

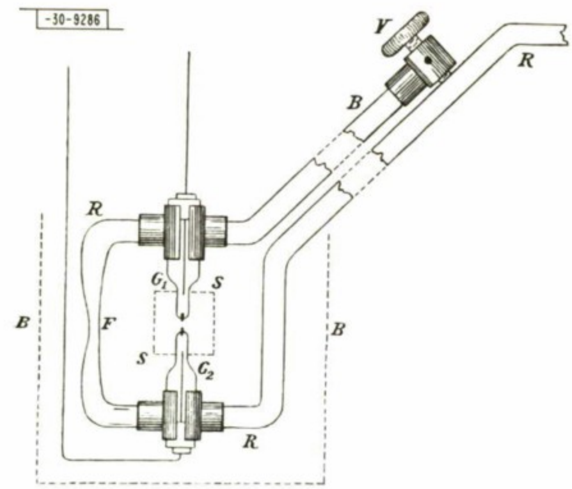

Fig. 1. The spark-excited Hertz dipoles used by P. N. Lebedev to generate radiation at millimeter wavelengths. The resulting electromagnetic waves were noiselike and covered a broad band of frequencies near the resonant wavelengths of the dipole. (Figure 3 from: P. N. Lebedev, Ann. Physik. Chem. 56, No. 9, 1 (1895).)

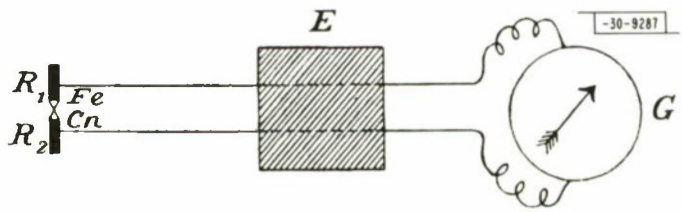

Fig. 2. Lebedev's detector shown here was the millimeter wave equivalent of the familiar radio frequency hot wire ammeter. (Figure 2 from: P. N. Lebedev, Ann. Physik. Chem. 56, No. 9, 1 (1895).)

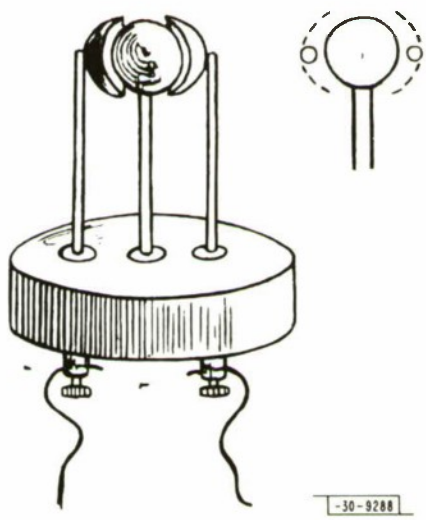

Fig. 3. J. C. Bose used a spark discharge between spheres as shown here to develop millimeter wavelength radiation. (Figure 2 from: J. C. Bose, Collected Physical Papers (Longmans, Green, New York, 1927).)

"Today millimeter wave research is in a similar position to that existing in the 1890's. It does not know where it is going. Any objectives it seems to have are scientific as it was with the Hertzians. Generation of the waves presents a formidable difficulty. Detectors are almost as crude as those of the early experimentalists, and the only positive application that may appear now is hollow pipe waveguide communications. Radar and wireless communications are beset by propagation difficulties."

All too true. We might note, however, that hollow pipe communications at millimeter wavelengths, long under intensive study at the Bell Telephone Laboratories, have now been shelved. The work is being carried on in Europe, and BTL has turned its attention to laser light-beam communications in hollow pipes! A sign of the times!

III. EARLY MILLIMETER WAVE RESEARCH

Let us now consider some of the early millimeter wave apparatus. Figure 1 shows the generator used by Peter Lebedev. A pair of radiators, a little over a millimeter long and about a half millimeter in diameter, is sealed into the ends of a glass tube. The spark gap between them is about 0.2 mm, and the two radiators are in turn excited via the spark gap between them and the lead wires. Excitation was by means of an induction coil sparked at about 30 per minute. This effective source of 6-mm waves had problems common to all spark gaps: they didn't survive a large number of sparks and had to be replaced frequently. Lebedev was able to do experiments with polarized waves. He measured the index of refraction of materials in the form of prisms. He built a Nicol prism to serve as polarizer and analyzer for 6-mm waves. The Physics Institute in Russia, named for Peter Lebedev, has built the 22-meter radio telescope so successfully in operation at millimeter wavelengths. This is the largest antenna so far to operate at millimeter wavelengths with reasonable efficiency.

Lebedev's detector is shown in Fig. 2. It is essentially a hot wire RF ammeter. He formed a thermoelectric junction with resonant elements R_1 and R_2. The thermoelectric current was measured with a galvanometer.

Figure 3 shows the apparatus that Bose used to work at 5 mm. He had rather portable apparatus, and was probably the first to launch millimeter waves in a circular waveguide. It is likely that he was exciting the TE_{11} mode predominantly, and possibly higher modes. The whole apparatus was enclosed in a shielded box, and served as his transmitter.

A millimeter wave spectrograph used by Bose is shown in Fig. 4. To make a polarizer, he wound fine wire around a piece of mica to form a grating. These wires were fixed in place with wax. Bose's receiver was a coherer enclosed in cylinder C. Bose also found that his spark gaps didn't work reliably very long. He wisely used a single discharge of his induction coil for a particular measurement, thus permitting many measurements before he had to refurbish his radiator.

In Fig. 5, we have an example of a mass radiator, as developed by Mme. Glagoleva-Arkadieva. Small particles suspended in oil are carried into the spark discharge by the rotating wheel. Excited by the spark discharge, the particles radiate at wavelengths somewhat commensurate with their size. The spectrum can be changed by changing the particle size. In the 1930's, radiations corresponding to parameters of the copper lattice were observed when copper particles were excited in an electric spark. The nature of the operation of mass radiators is still not well understood, and the further investigation of this phenomenon in light of what we know about solids today might well lead to some interesting research.

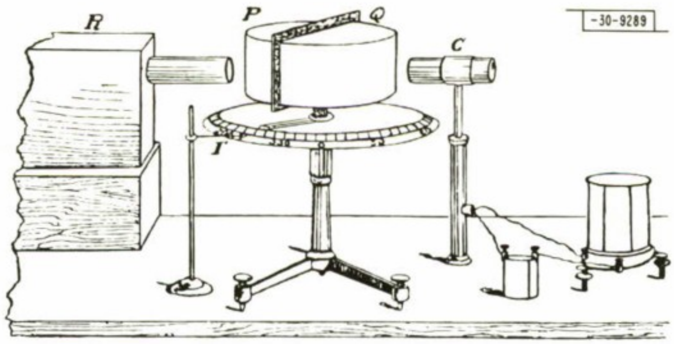

Fig. 4. The experimental arrangement used by Bose to study polarization effects in solids and liquids at millimeter wavelengths. (Figure 1 from: J. C. Bose, Collected Physical Papers (Longmans, Green, New York, 1927).)

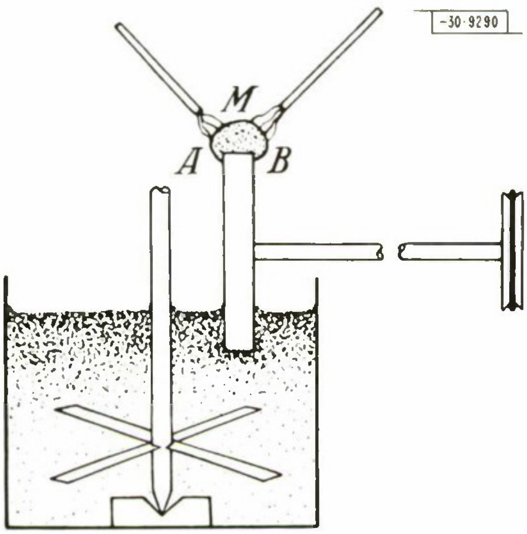

Fig. 5. To reduce the size of the spark-excited radiators, Mme. Glagoleva-Arkadieva used filings suspended in oil and carried into the discharge by a rotating wheel. Radiation wavelengths were observed to correspond to the size of the particles used. (Figure 1 from: A. Glagoleva-Arkadieva, Z. Physik, 55, 234 (1929).)

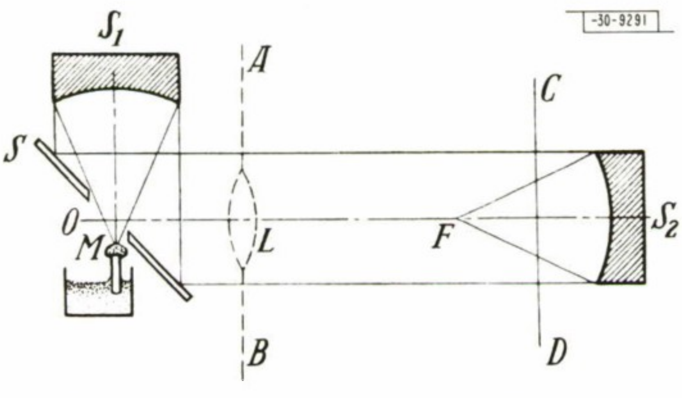

Fig. 6. The spectrograph arranged by Mme. A. Glagoleva-Arkadieva for studies at millimeter wavelengths. This is an arrangement of mirrors commonly used in far infrared spectroscopy today. (Figure 2 from: A. Glagoleva-Arkadieva, Z. Physik. 55, 234 (1929).)

In Fig. 6, we have a diagram of Mme. Glagoleva-Arkadieva's spectrograph. The arrangement of the mirror system is very familiar to infrared spectroscopists. The output of the mass radiator is collimated through an active region and thence into a detector at the focus of a receiving mirror. A popular form of detector for Bose and many of the later workers was the eoherer. Bose used a eoherer of fine coiled springs. The springs were laid in a shallow notch in a bakelite holder in a way that the pressure on their mutual contact could be varied. The radiation falling in the coherer changed its resistivity, and this change was measured by a galvanometer.

IV. THE PRESENT AND THE PROMISE

So mueh for the past. What about the present? Where is the millimeter and submillimeter gap? Why has it persisted so long? Why is it important to fill the gap with devices and techniques? These and many other questions have been considered in the past and are still questions today. Some have been answered. Townes' inspired concept of the maser grew out of thoughts about how one might provide coherent radiation in the millimeter and submillimeter regions. As a result, we have wonderfully coherent sources in the visible and near infrared regions, and inroads are being made on the 100-micron (0.1-mm) region. We have built masers at 8 and at 4 mm, but their operation has been difficult enough to diseourage their pragmatic use. In a very real sense, the gap prevails.

Where is this gap in the overall electromagnetie speetrum? Figure 7 shows it to be substantially in the center of a chart of the EM spectrum, truncated a few decades on eaeh end.

Why bother about millimeter waves? Scienee and technology respond a bit differently. Scientific reasons for interest in millimeter waves include the following:

New Spectrum:– Because nature has spread the location of energy levels over a wide region, freedom to ehoose any part of the EM speetrum for speetroseopie purposes lends flexibility to

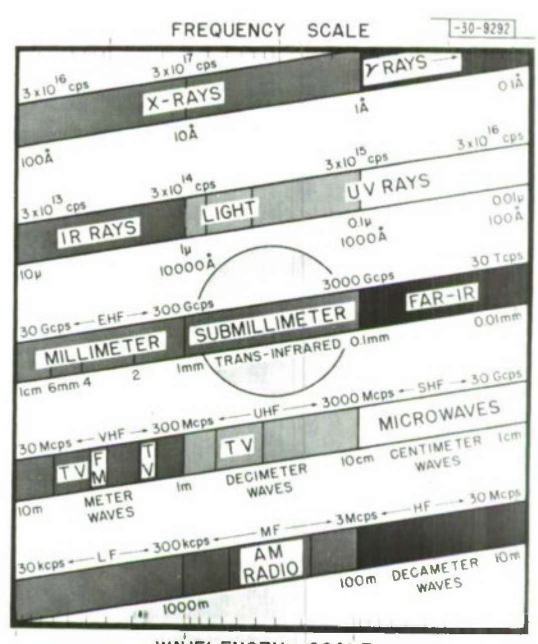

Fig. 7. Fifteen decades of the electromagnetic spectrum. Note that each octave contains the same absolute bandwidth, the same channel capacity, as the entire spectrum below it!

our investigation of matter. The spectra of gaseous molecules, solid state materials, and plasmas lie in the millimeter region.

Higher Photon Energy:– The millimeter wave photon has higher energy than its microwave counterpart, and can thereby excite carriers, for example, across larger energy gaps. The photon energy is comparable to that manifested in exchange and anisotropy fields in antiferromagnetics, and is comparable to what is termed the energy gap for certain superconductors.

Better Resolution:– For cyclotron resonance in semiconductors, for example, the width of the resonances is proportional to $1/\omega\tau$, where ω is the cyclotron frequency (eH/m^*c) and τ is the lifetime of the carriers. If $\omega\tau$ is not greater than one, no resonance is observed. For short lifetime materials, a high frequency is clearly required. As was the case for the ammonia inversion spectrum, it is often better to observe these phenomena at their fundamental frequency than to deduce the level splitting from high resolution infrared measurements on spectral lines originating from higher levels.

Coherent Sources:– Sensitive spectroscopy is dependent upon good detectors and efficient sources. The coherent source develops all its intensity in a narrow frequency band, thereby producing an output manifold better than a filtered broad-band source. Controlled coherent sources also contribute to higher resolution.

The engineer, on the other hand, sees the millimeter wave region in a slightly different light. He sees:

> Uncrowded Spectrum:– Possible relief from the severe crowding in the lower frequency regions;
>
> Large Bandwidths:– When it is observed that a 10-percent bandwidth in the millimeter region encompasses the same range as a whole decade of frequencies at ten times the wavelength, some impression is gained of the tremendous channel capacity available.
>
> Angular Resolution:– The prospects of getting narrow antenna beams with relatively small antennas is an attractive one, particularly where space is at a premium. It is at millimeter wavelengths that we can think in terms of beams with fractional milliradian spread and the angular resolution that goes with it, while working with antenna apertures of 10 meters in diameter or less.
>
> Reduced Interference:– The millimeter wave region is relatively quiet: not many computing services, no ignition noise problems, and atmospheric absorption can act as a shield. Space-to-space communication at a wavelength strongly absorbed by the atmosphere would be free of earth-based interference and immune to earth-based interception.

Atmospheric propagation has often been the major obstacle in the way of systems applications of millimeter waves. Ground-based applications will employ propagation paths essentially parallel to the ground. Figure 8 illustrates the attenuation that will be encountered over such paths and under the indicated conditions. There are a number of noteworthy characteristics of these curves. First, one sees the existence of "windows" of small attenuation with minimal attenuation at wavelengths of about 8, 3, 2.3, 1.25, and 0.8 mm. Note also the upward trend of the opacity of these windows as the wavelength is decreased. The attenuation in the 8-mm window is less than half that in the 3-mm window. Second, note the sizable reduction in opacity of the windows for an altitude of 4 km. The regions of minimum opacity shift slightly also, as the absorption lines narrow at reduced pressure. Third, note the great attenuation of oxygen at 5 mm.

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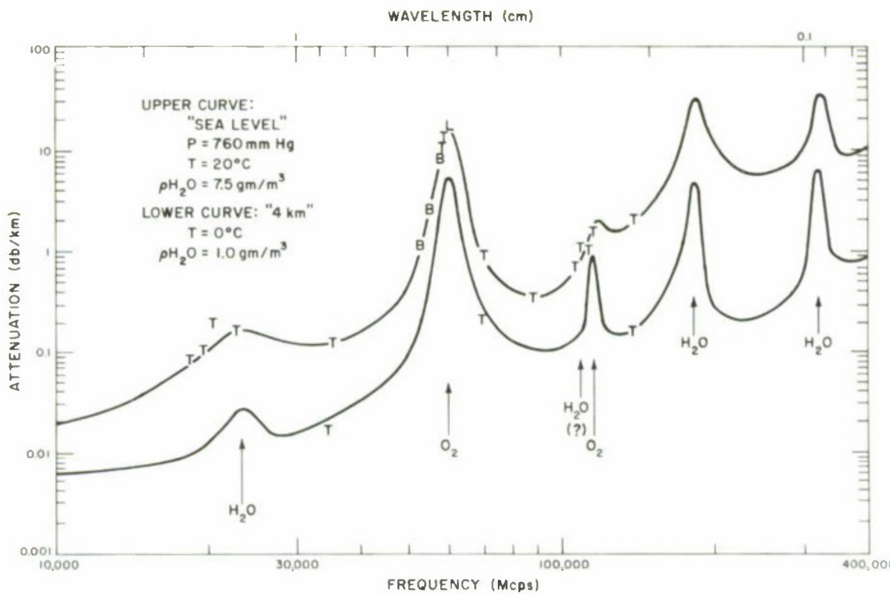

Fig. 8. Attenuation in the clear atmosphere per kilometer for horizontal propagation.

All is not lost on account of these absorptions, however, because careful measurement of these absorption lines, particularly from above the atmosphere, permits continuous monitoring of the gaseous content of the upper atmosphere.

There is much yet to be learned about propagation in the atmosphere, particularly at millimeter and submillimeter wavelengths. In the exploration of this problem, I am sure that we shall develop techniques and instrumentation of great interest to meteorologists.

Figure 9 shows the one-way attenuation through a specified atmosphere at near-zenith angles. What is revealed in this figure is that the system looking out into space or back to earth suffers far less from atmospheric opacity. While the system would by no means be all-weather, earth-satellite and satellite-earth links are entirely feasible.

V. COMMUNICATIONS AND RADAR SYSTEMS

The system range equations deduced at longer wavelengths hold equally well for millimeter waves. Ignoring propagation problems for the moment, the range of a communications link or beacon system is given by

$$R^2 = \frac{\hat{A}_t \hat{A}_R}{\lambda^2} \frac{P_t}{P_R} \quad ,$$

where R is the range, λ the wavelength, P_t the transmitter power, P_R the minimum receiver power required to pass the required information, and $\hat{A}_t$ and $\hat{A}_R$ the effective areas of the transmitting and receiving antennas, respectively. The equation was written purposely, and perhaps deceptively, in a way that indicates range proportional to one over the wavelength. As the wavelength decreases, however, antennas must be made more precise to maintain effective area, and transmitter power becomes harder to develop. Actually, the above equation can be written to show no wavelength dependence at all:

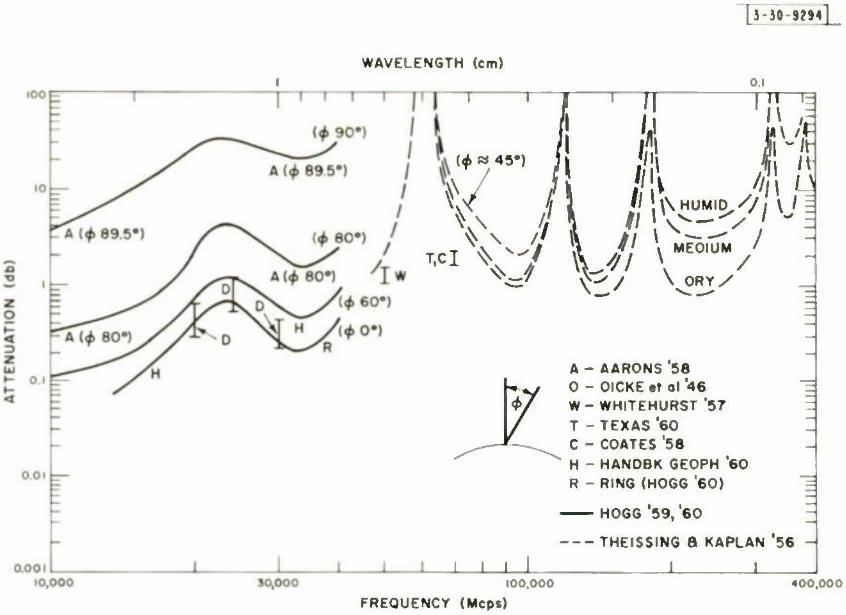

Fig. 9. Total attenuation for one-way transmission through the clear atmosphere as a function of the zenith angle.

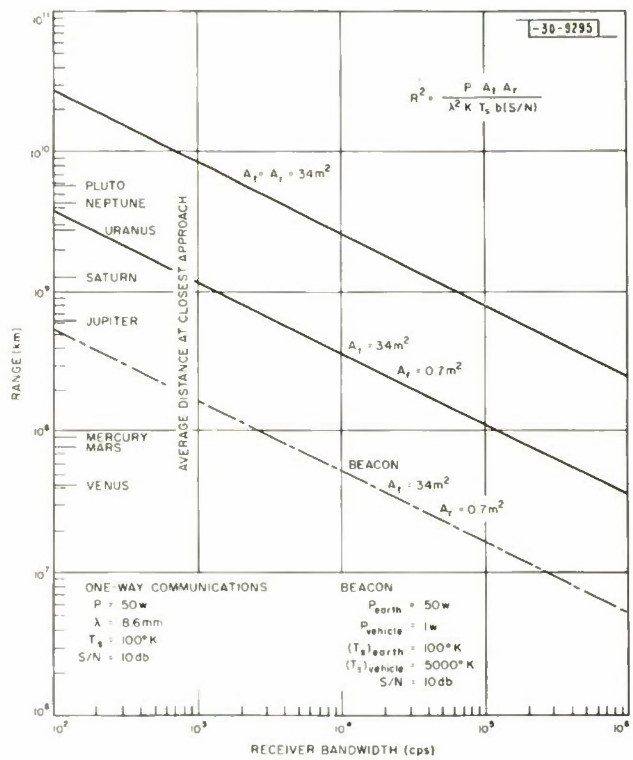

Fig. 10. Limiting communications and radar-beacon ranges under ideal propagation ranges and with the system characteristics shown, as a function of receiver bandwidth.

$$R^2 = \frac{G_t \hat{A}_R}{4\pi} \frac{P_t}{P_R} \quad ,$$

where G_t represents the gain of the transmitting antenna.

Similarly, one can write the radar and scatter communications equation as

$$R_t^2 R_R^2 = \frac{\hat{A}_t \hat{A}_R}{\lambda^2} \frac{P_t}{P_R} \frac{\sigma}{4\pi}$$

for the case where the scatterer has an isotropic scattering cross section σ and this scatterer does not fill the antenna beams. The ranges from the transmitter R_t and from the receiver R_R have been written separately to allow for bistatic operation. Again the $1/\lambda$ range dependence can be eliminated by substituting antenna gain for effective area. Moreover, in those instances where the scatterer fills the antenna beam, the total scattering cross section increases with range because the illuminated area does, and there results an R^2 dependence on range rather than the R^4 dependence indicated above.

Radar and communications scatterers do not always seatter isotropieally – in faet, they rarely do – in which case the cross section, σ, contains a directional "gain" function and reflection coefficient, the former being normalized to isotropic scattering. In the troposphere, for example, the scattering is believed to be largely forward with an angular function or pattern related to the graininess of the atmospheric turbulence. Tropospherie scattering experiments performed at millimeter wavelengths might well demonstrate the possibility of millimeter wave communications by this scattering technique.

Armed with these equations and ignoring propagation problems, one can calculate prodigious ranges for systems having modest transmitter powers and antenna apertures as shown in Fig. 10. Clearly, long ranges can be expected. How ean one devise a ground-based test to illustrate this potential? In our case, this test took the form of the design of a millimeter radar capable of deteeting the moon. Because the moon scatters such a small fraction of the incident power and because it is at a reasonably long range, far enough to be called a space hop, an 8-mm moon radar should demonstrate rather well the capability of millimeter waves in space applications.

VI. RADAR ASTRONOMY OPENED AT MILLIMETER WAVELENGTHS

One of the first problems, of course, is to obtain the necessary components of the system. Preliminary estimates indicated that a large antenna (10 to 30 feet in diameter), a reasonable amount of power (10 to 100 watts), and a sensitive receiver would be required. The maximum of all these would not have to be achieved simultaneously. A eomparison with the Soviet radars described in the literature is given in Table I.

A preeision surfaee on a 28-foot parabolie mirror was obtained by borrowing a triek from the astronomers. Sir Isaac Newton observed that the surface of a rotating liquid became parabolie under the influence of gravitational and eentripetal forces. The idea is illustrated sehematically in Fig. 11. R. W. Wood at the turn of the century used this principle to build a zenith optieal teleseope by rotating a tray of mereury. The focal length of the spun mirror is a funetion of the rotational speed of the fluid as shown. A top quality surfaee, of eourse, depends on one's ability to control the rotational speed, rumble of the turntable, vibration, and the like. Wood installed his telescope in a pit as shown in Fig. 12, to give it some protection from these

TABLE I

COMPARISONS OF CW MICROWAVE MOON RADARS*

	Parameters	Russian S-Band	Russian X-Band	8-mm System
D	Antenna Diameter (feet)	13.2	15.7	28
	Antenna Beamwidth (deg)	1.7	0.5	0.06
	Antenna Gain (db)	39	51	67
f	Frequency (kMcps)	3	10	35
p	Power (watts)	1000	2,500	20
T	System Noise Temperature (°K)	5100	11,800	450
b	IF Bandwidth (kcps)†	1200	3,600	3
t	Integration Time (seconds)	60	60	2
Q	Performance Ratio (db) (8 mm = 0)	−33.4	−22.1	0

* From: V. L. Lynn.

† It should be noted that most of the poor performance of the Russian systems with respect to the 8-mm system is due to the extremely wide bandwidths reported. If our knowledge of their values should be in error by as much as two orders of magnitude, the comparison would be closer by 10 db.

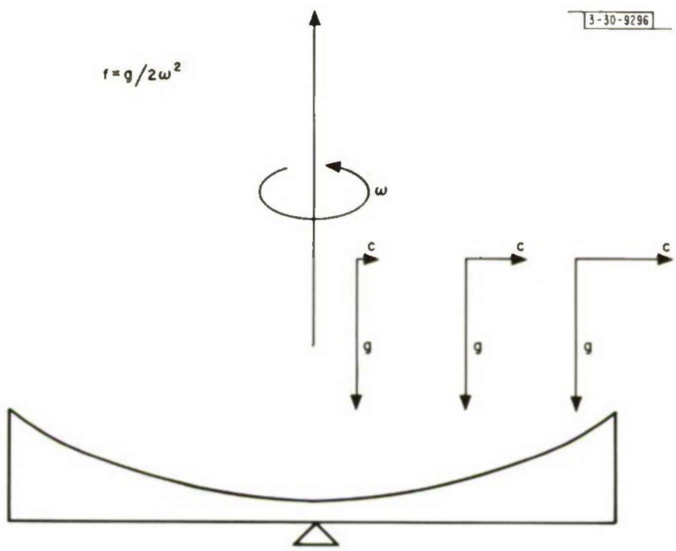

Fig. 11. Schematic of the action of gravitational and centripetal forces on a rotating liquid producing a parabolic surface.

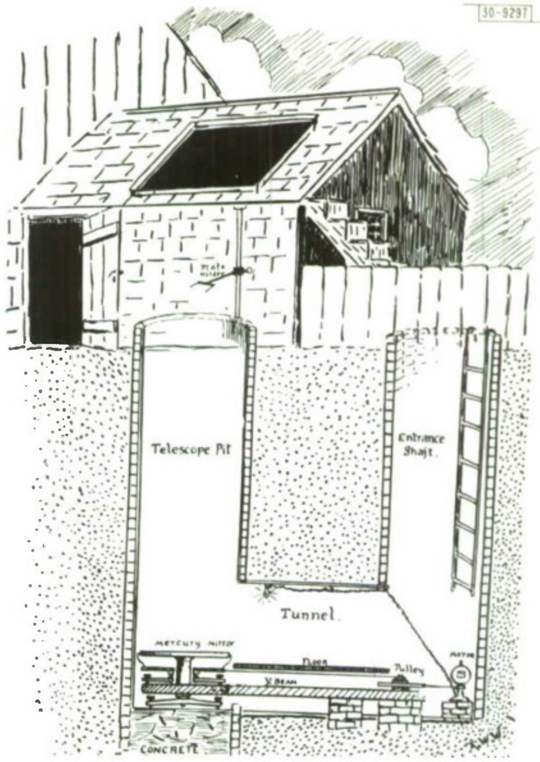

Fig. 12. The zenith telescope employing a mercury paraboloid devised by R. W. Wood. (Figure 5 from: R. W. Wood, Astrophys. J. 29, No. 2, 164 (1909).

problems. The D. S. Kennedy Company used this technique to cast a precision plastic surface on a suitable 28-foot-diameter backup structure. This surface, made conductive with a sprayed coating of molten zinc, was weatherproofed by a second layer of plastic.

A large precision antenna, once built, has to be fed. Adaptation of the optical method due to Cassegrain is a popular approach these days. The geometry of the ray optics of both the Cassegrainian (secondary a hyperbolic surface of revolution) and the Gregorian (secondary an elliptical surface of revolution) systems is illustrated in Fig. 13. This figure shows that a satisfactory configuration for the secondary reflector is a flat plate. It also shows that a flat plate would cause much aperture blocking. The choice of a smaller secondary, on the other hand, would require a larger feed horn. An optimum design in this configuration is the choice of a secondary reflector size such that the aperture blocking is minimal and is identical with the aperture size of the required feed horn. We also have the option of moving the focal point of the feed horn closer to the focal point of the parabola. When this is done, Fig. 14 shows that a small flat plate serves as a satisfactory secondary reflector of a modified Cassegrainian system. The result, developed for our 28-foot antenna by K. Keeping, is a circularly symmetric feed system having minimal aperture blocking. We have accomplished this by accepting more loss in the longer run of circular waveguide to the feed. Oversized TE_{11} guide has satisfactory loss characteristics. One point of caution: if the flat plate is too close to the feed, it will form a ring image of the point source in the feed and result in unsatisfactory illumination of the main parabola. Figure 15 shows a feed of this type fitted into a small millimeter wave antenna. The flat plate secondary is shown supported by a foam hemisphere. The complete 28-foot antenna installation is shown in Fig. 16.

Equipped with this large antenna, we can turn our attention to the development of a reasonable amount of power at 8 mm. The floating-drift-tube klystron shown in Fig. 17 was the best

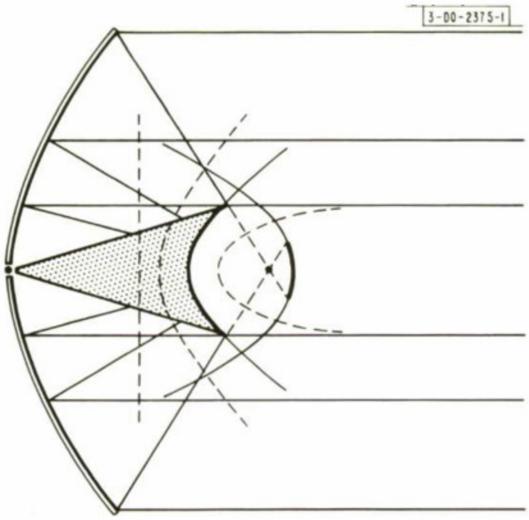

Fig. 13. The generation of the surface of a secondary reflector for illuminating a paraboloid primary by the family of hyperbolae of rotation (Cassegrainian) constructed between the foci of the feed and the parabola or by the ellipsoids of rotation (Gregorian) is illustrated in this drawing of the geometric optics of conic sections.

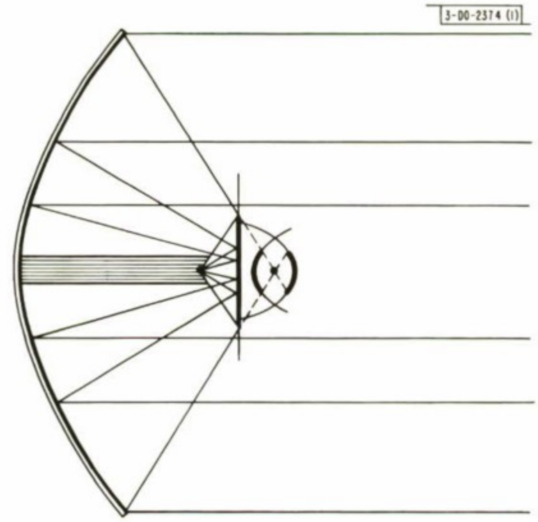

Fig. 14. The evolution of the flat surface (plane hyperboloid secondary) as a modified Cassegrainian optical system.

Fig. 15. The Keeping feed installed in a four-foot spun-cast parabola. The unit served as a transmitter for the pattern range employed in the evaluation of the 28-foot parabola.

Fig. 16. The 28-foot precision parabola developed using spin-casting techniques.

Fig. 17. Flooting-drift-tube klystron oscillotor used os the power tube for the 8-mm rodor. V. L. Lynn, Project Engineer, is shown holding the millimeter wave power tube.

we could do. When stabilized to about one part in 10^9 by a frequency-phase lock system, this tube delivered 12 watts CW, not very much for the job we set out to do, but it turned out to be enough.

The parameters of the moon radar as it evolved are given in Table II. Our antenna was larger, the transmitted power smaller, and the receiver sensitivity less than what we had originally hoped for, but a detection resulted.

VII. RADAR OBSERVATIONS OF LUNAR SCATTERING

Most radar observations of the moon have been made with antenna beams larger than the angular extent of the moon. Our narrow radar beam (about 1/10 the angle subtended by the moon) allowed angular resolution of the more prominent features of the moon, the maria, and the terrae. Figure 18 shows the points on which we chose to center the beam.

The experiment was a simple CW measurement of the scattering of the lunar surface in the beam at a wavelength of 8 mm. After the transmitter had been on for a few seconds, it was turned off and the receiver switched in. The receiver output was post-detection integrated for 2-1/2 seconds, a nominal round trip time for the radar signal. About 10 of these 2-1/2-second "exposures" were then averaged by hand to give the results indicated in Fig. 19. Very little of the limb darkening so evident at meter wavelengths is shown here. It is clear that the moon appears quite rough at a scale of about 8 mm.

VIII. BEYOND THE MOON

Radar astronomy on any of the other planets will require upwards of 50-db more performance from the radar. Clearly, extension of millimeter wave radar astronomy beyond the moon is a rough road. Greater radar sensitivity, however, would do much to sharpen our measurements on the moon at millimeter wavelengths.

In radio astronomy, millimeter wavelength observations represent a new frontier. At the longer wavelengths, radio telescopes are resolution limited, that is, radio sources are small

TABLE II RADAR AND PATH PARAMETERS	
Frequency	34,990 Mcps
Wavelength	8.57 mm
Peak Power	12.0 watts
IF Bandwidth	170 cps
Spectrum Bandwidth	
Combined Instability of Transmitter and Local Oscillator	<100 cps/2.5 sec
Libration Spread Across Half-Power Beamwidth During Observations	82 – 131 cps
Receiver	
Mixer Noise Temperature	3300°K
Noise Figure	10.9 db
Video Integration	~2.5 sec
Distance to Moon	3.98×10^8 m
Losses	
Plumbing, Two-Way	3.8 db
Estimated Mean Atmospheric	0.3 db

enough and close enough together to require resolution, but are powerful enough radiators of long wavelengths to lessen the sensitivity required. When the sensitivity of a completely filled-in aperture is not required, resolution can be provided by interferometer techniques. The spectral indices of most radio sources display a sharp decrease in flux emitted as the wavelength of observation is shortened. Millimeter wave radio astronomy is therefore both resolution and sensitivity limited. We need a large effective area for resolution, and we need that area densely filled for the sensitivity provided by a large collecting surface.

A fascinating mystery has developed around the observations at millimeter wavelengths of the radio source in Taurus A. The Russians, working at 8 mm with their 22-meter Lebedev antenna, observed what appeared to be a second source near the main radiation peak. Soon afterward, Alan Barrett looked at Taurus at 16 mm, but was unable to find a second source. Observations at Lincoln Laboratory at 8 mm initially showed what might be regarded as evidence of a second source (Fig. 20). Barrett, on a recent trip to the USSR, learned that the Soviets had repeated their experiments and hadn't seen the second source but, since our report had been published meanwhile, they chose not to publish theirs. Measurements of the University of California group near 21-cm wavelength reveal no second source, but workers at Aerospace, using their 15-foot parabola at 3 mm, report evidence of a second source. The tale ends there, but it should be interesting as more measurements are made and the mystery either deepens or is solved.

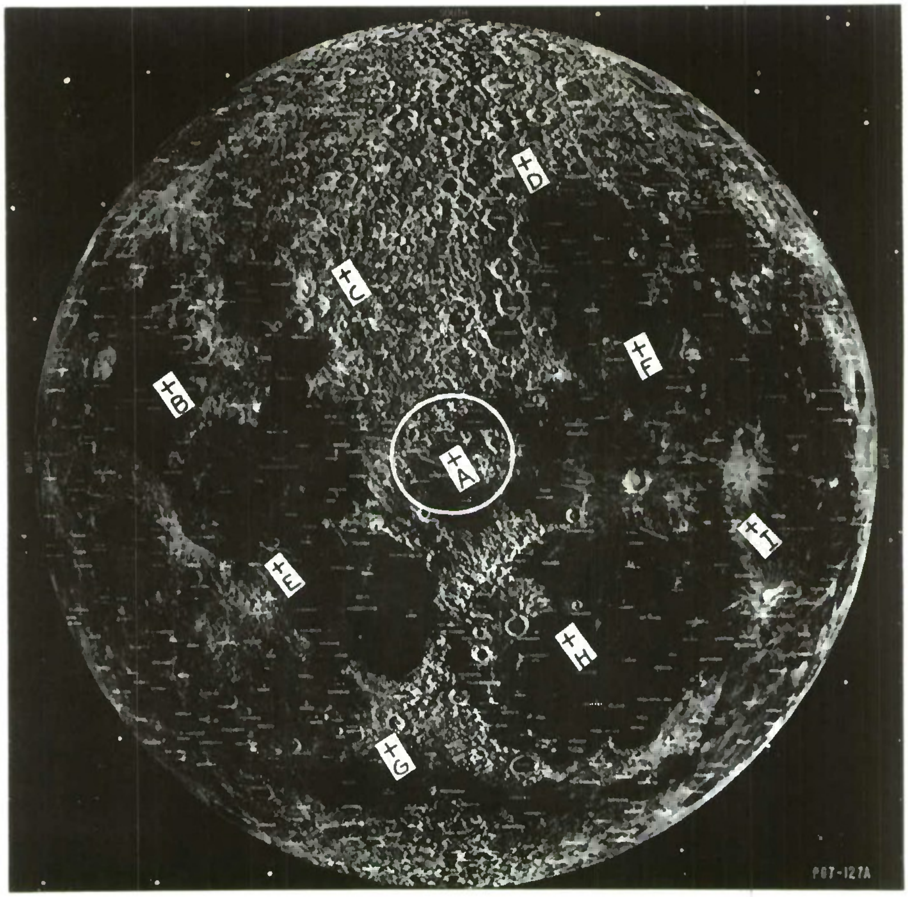

Fig. 18. The moon showing centers on which the radar beam was focused during observations. The circle around A indicates the beam size relative to that of the moon.

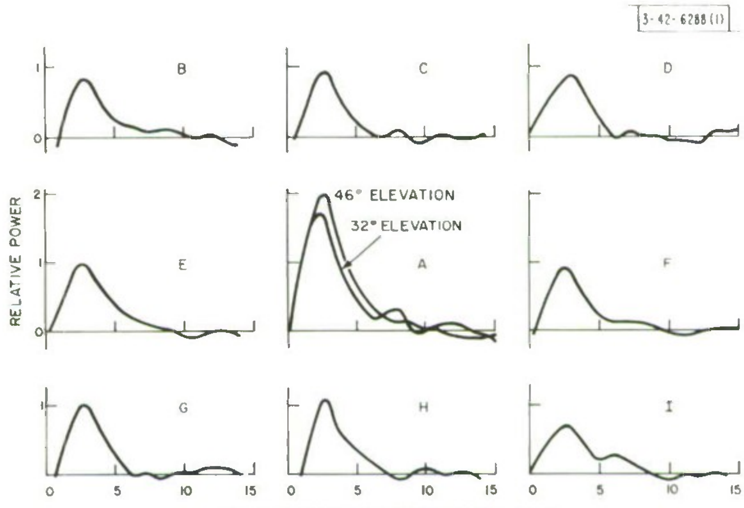

Fig. 19. Relative power reflected from the nine centers on the moon shown in Fig. 18. Little difference in reflectivity was observed at the various centers located on widely differing surface features.

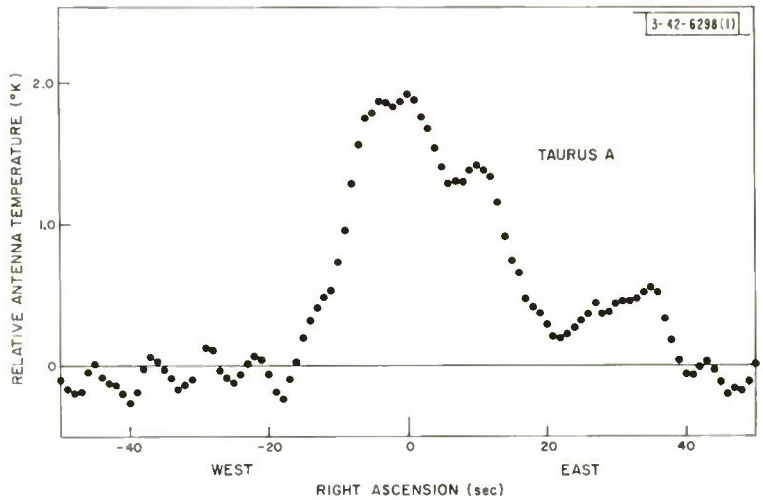

Fig. 20. An 8-mm-radiometer drift scan of the radio source in Taurus A.

TABLE III

LARGE MILLIMETER WAVE ANTENNAS

In Operation	Diameter (feet)	Operating Wavelength (mm)	Efficiency (percent)
Naval Research Laboratory	50	8	25
Naval Research Laboratory*	10	4	
Lincoln Laboratory	28	8	17 (at 3.2 mm)
Radio Research Establishment	16	3	
Lebedev Physical Institute	72 (22 m)	8	25 ($A_{eff} = 100\ m^2$)
Ewen Knight	28	8	
University of Texas	16	2	
Air Force Cambridge Research Laboratories	29	8	
Aerospace	15	3	
University of London	15	1	
Future			
North American Aviation (Columbus)	30	3	
NRAO Kitt Peak (altitude, 6800 feet)	36	1.2	
Haystack (1 minute of arc, 73 db)	120	8	

* Although not large by present standards, this antenna is listed because it was the first of its kind.

IX. OTHER USES

There are many other sources of interest to the millimeter wave radio astronomers and quasars are among them.

There has been activity in the military and commercial radar field. High resolution radars at 8 mm for harbor and airport runway surveillance have been built here and abroad. Millimeter weather radars have also been built. None of these have seen widespread use so far.

We have masers at millimeter wavelengths and good prospects for parametric amplifiers at 8 mm. We have power tubes that develop as much as a kilowatt CW at 8 mm, and 100 kw (inside the tube) have been the peak power developed at 3 mm. Support of this work has been sporadic and results, as one might expect, have followed suit.

There have been a number of good review papers on millimeter waves. A list appears at the end of this report. In addition, a tabular list of large millimeter wave antennas has been prepared and appears in Table III.

X. NOW WHITHER

Now, what about the future? There is clear evidence of an upturn of interest. NASA is supporting propagation investigations in industry. The future for radio and radar astronomy, as I have indicated, appears to be bright. High resolution radars riding space vehicles can be most useful in the future. Our attempts to achieve controlled thermonuclear reactions are aided with millimeter wave techniques. Spectroscopy of the earth's atmosphere and the study of weather phenomena are fields for millimeter waves. The passive detection of icebergs at night appears to be a pragmatic application. Millimeter waves still offer new horizons to solid state research. Millimeter waves have been suggested in connection with the detection of clear air turbulence. The list goes on and on.

A word of caution: Let us not continue to seek problems for the millimeter wave solution. Instead, let us seek solutions to problems using millimeter wave techniques. The former results often in strained, ill-connected solutions; the latter to the natural evolution of a good fit to the nature of the problem. This approach is not likely to remove the cyclicity in millimeter wave research and development, but it will certainly lessen the depth of the valleys in that cycle.

ACKNOWLEDGMENTS

This report derives much from the work of V.L. Lynn, M.D. Sohigian, E.A. Crocker, and M.L. Meeks. Details have been published in the form of a technical report [V.L. Lynn, M.D. Sohigian, and E.A. Crocker, "Radar Observations of the Moon at 8.6-mm Wavelength," Technical Report 331, Lincoln Laboratory, M.I.T. (8 October 1963)] and two journal articles:

V. L. Lynn, M. D. Sohigian, and E. A. Crocker, "Radar Observations of the Moon at a Wavelength of 8.6 millimeters," J. Geophys. Res. 69, 781 (February 1964).

V.L. Lynn, M.L. Meeks, and M.D. Sohigian, "Observations of Venus, the Region of Taurus A, and the Moon at 8.5 millimeter Wavelength," Astronom. J. 69, 65 (February 1964).

The excellent recording of the seminar mode by Gordon Holland and Roy Mitchell facilitated its transcription into written form.

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DOCUMENT CONTROL DATA – R&D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)* Lincoln Laboratory, M.I.T.	2a. REPORT SECURITY CLASSIFICATION Unclassified 2b. GROUP None
3. REPORT TITLE Millimeter Wave Research: Past, Present, and Future	
4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)* Technical Report	
5. AUTHOR(S) *(Last name, first name, initial)* Meyer, James W.	

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
17 May 1965	28	8

8a. CONTRACT OR GRANT NO. AF 19(628)-500 b. PROJECT NO. c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) Technical Report 389 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)* ESD-TDR-65-72
10. AVAILABILITY/LIMITATION NOTICES None	
11. SUPPLEMENTARY NOTES None	12. SPONSORING MILITARY ACTIVITY Air Force Systems Command, USAF

13. ABSTRACT

This report is the edited transcript of a seminar given at Lincoln Laboratory on 2 March 1965. The cyclicity of interest in millimeter wave research is traced from the time of Hertz, when investigations of this part of the electromagnetic spectrum began. The waxing and waning of millimeter wave research are traced as exciting new fields are discovered which diverted the interest of physicists. Each re-emergence of millimeter wave research has been more robust, often because the results of the diversions were important to improved techniques. Early millimeter wave apparatus is described. The narrative of the development of a millimeter wave radar for the detection of the moon relates the opening of this spectral region to radar astronomy. Other applications are mentioned, along with future possibilities. A chronology, a list of large millimeter wave antennas, and a bibliography of review papers are included.

14. KEY WORDS

millimeter waves
microwaves
solid state physics
electromagnetic propagation
spectrum analyzers